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Coordinated Control of an Isolated DC Microgrid with Dynamic Source Variation and Wide Load Fluctuation

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Abstract : It is observed that rapid variations in source power and load demand of an isolated DC microgrid affects the DC link voltage as well as AC side voltage and frequency profile during transient conditions. This paper proposes a SOC based power management technique for coordinated control of an isolated DC microgrid to maintain the DC link voltage almost constant with both source and load side variations. The effective droop control technique is also used in the work to regulate the voltage and frequency at the point of connection (PC) within a permissible limit. An isolated microgrid comprising of wind, solar photovoltaic (PV), battery, fuel cell and aqua-electrolyser is considered here for study. In this isolated system, a permanent magnet synchronous generator (PMSG) based variable speed wind energy conversion system (WECS) and a solar PV energy conversion system (PVECS) is used as primary energy sources. Coordinated control operation of fuel cell - electrolyser and battery is used to recycle the surplus power in the system, thus regulating frequency. The simulated results show an effective power management in the presence of source dynamics and load variation with negligible dc link voltage fluctuation. Voltage and frequency fluctuations at PC show the effectiveness of the inverter droop controller. The simulation study is carried out in MATLAB/ Simulink environment.

Keywords : Power management, MPPT, Isolated microgrid, Droop control, Coordinated control.

1. INTRODUCTION

Nowadays, renewable energy based standalone power system draws more attention where transportation of electric power through grid extension may not be possible due to economic reasons. Because of less environmental impact, the renewable energy based microgrids are gaining popularity as a power generation system to meet the end user demand. However, considering the standalone mode of operation renewable energy sources (RES) may not be sufficient to meet the end user demand due to their intermittent nature. But proper coordination of energy storage systems (ESS) with RES using microgrid technology [1, 2, 3] makes them dispatch-able power source.

Integration of renewable distributed energy resources (DER) into power systems maintaining reliability and utilization of complete potential in distributed generations is quite a challenging task [2, 3]. Concept of microgrid was brought in as a solution to overcome the challenges of reliable integration of DERs, ESSs and controllable loads. Microgrid can operate in both grid connected and isolated (standalone) mode and also capable of transitions between these two modes [2]. Grid connected microgrid exchange deficit or excess power with the host grid. Whereas isolated microgrid supply the local loads by maintaining power balance between demand and supply with the help of storage units. Microgrid without point of common coupling (PCC) is called isolated microgrid where integration with host grid is not possible due to either technical or economical constrain [1]. Therefore, isolated microgrid enduringly runs in standalone mode only.

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Among various types of renewable energy resources, wind and solar, with huge potential and no impact on environment pollution, are generally taken as primary energy sources of microgrid because they act complementary to each other and no fuel cost is required for energy extraction [3]. When wind and solar energies are considered as primary energy sources, the intermittent nature of these sources should be taken into consideration. Therefore, to make a microgrid reliable using these kind of energy sources, a hybrid energy storage system (HESS) [1, 3], power conditioning interfacing devices and their control are necessary. There are several ESS available to store energy. Out of them pumped hydroelectric systems, compressed air energy storage (CAES), and hydrogen storage (fuel cell-electrolyser combination) generally have slow response time but can be used for long-term energy storage [1, 2,]. On the other hand, storage devices with fast response time, such as batteries, flywheels, super-capacitors, and superconducting magnetic energy storage (SMES), can respond in very short-time but loses its energy content very rapidly [4].

Among these storages, battery bank is widely used in microgrid application, because it has number of advantages [4]. But it has certain limitations also such as, frequent overcharging and undercharging reduces its lifespan drastically [3, 4]. Because of these limitations, controlled use of battery in coordination with long term energy storage is necessary for isolated microgrid applications. Presently, storing electric energy in the form of hydrogen for long term use is a very good option because it offers the lowest marginal cost and better operational efficiency [5, 6, 7]. Simultaneously, stored hydrogen can be used in multiple applications like hybrid electric vehicle, synthesizing of natural gas, etc. So hydrogen storage is one important aspect of research in present time.

To operate multiple ESS with RES in effective and coordinated manner [8], a power management system (PMS)/Energy management system (EMS) is necessary [3, 9]. In literature different researchers worked on PMS of a standalone/grid connected hybrid system with multiple ESS [6] – [10]. All of them mainly compared different power management strategies in terms of SOC management. But hardly there is any literature which shows very good DC link voltage profile considering dynamic source variation and wide load fluction simultaneously. Though some literature like [7, 10] reported on DC link voltage regulation and power quality but there are some limitations. This may happen because of improper coordinated operation of multiple ESS.

So in this paper, battery bank is used for longer period of time in coordination with fuel cell–electrolyser combination, which gives better DC link voltage profile, better power quality and reduces the individual rating.

The isolated DC microgrid considered in this paper constitutes PMSG based wind energy conversion system (WECS) [11, 12] and solar photovoltaic energy conversion system (PVECS) [13] – [17] as primary power generation system, battery energy storage system (BESS) [4] is used as primary storage device and fuel cell (SOFC) [18, 19] – electrolyser [7] combination is used as a backup generation and secondary storage system. All the energy conversion systems and storage systems are integrated through a common DC bus, using power electronics interfacing devices as shown in Fig. 1, which is finally connected to the load through Inverter and filter. The power extraction from WECS and PVECS are controlled by maximum power point tracking (MPPT) controller [15] – [17]. The battery controller with the help of PMS controls the DC bus voltage and PMS controls the coordinated operation of fuel cell – electrolyser with battery.

During fast transient conditions, such as high load fluctuations and wind and solar fluctuations, battery plays a key role to absorb the effects of transients created by those fluctuations. Therefore, a battery should remain in service for a longer period of time with power handling capacity to absorb fast transients and maintain DC link voltage. When SOC crosses upper or lower safety limit, to protect the battery health, battery controller stops any further charging or discharging accordingly. Under this situation it becomes very difficult for FC-electrolyser to regulate the DC link voltage. As a result, DC link voltage as well as AC output voltage degrades.

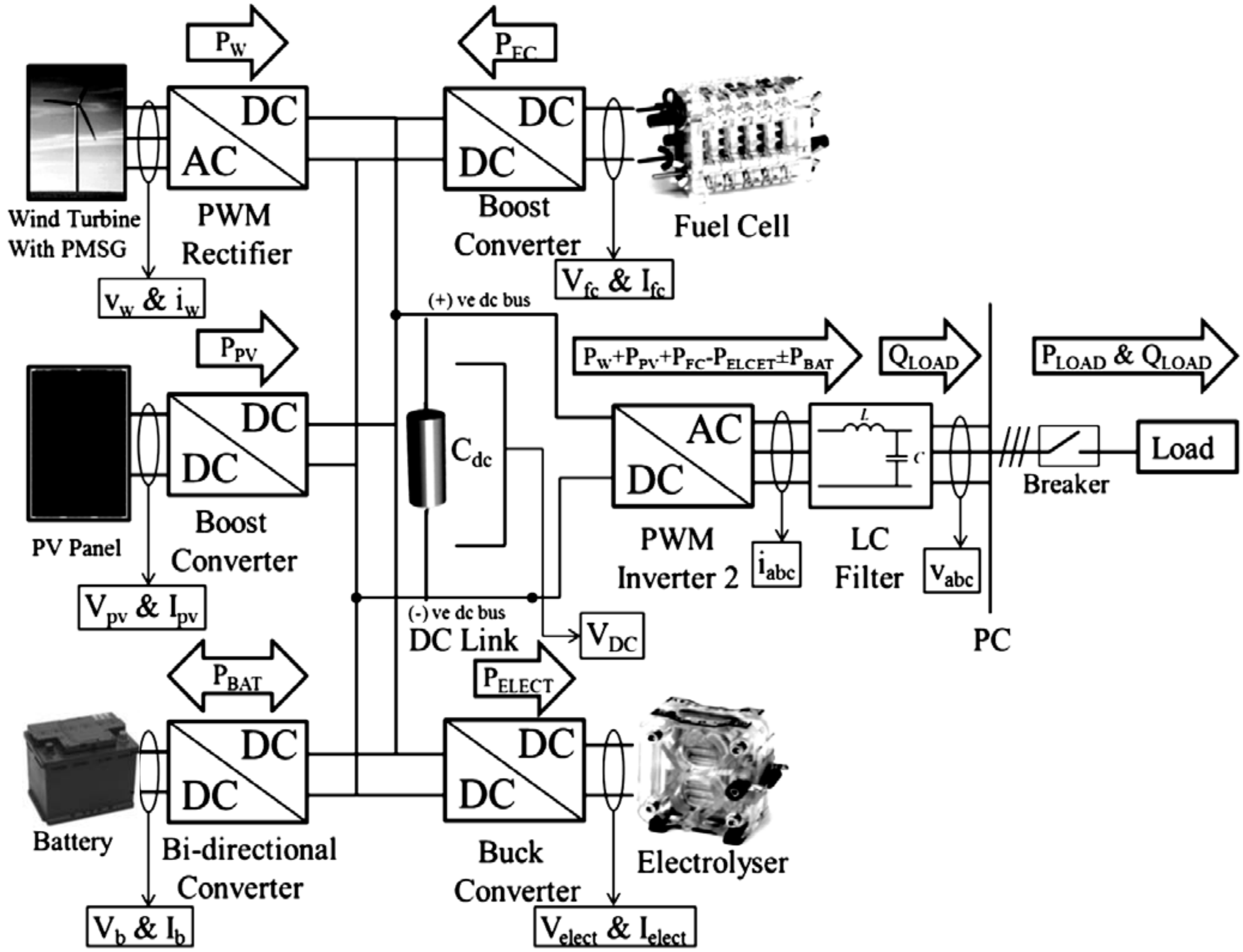

Figure 1: Structure of the isolated DC microgrid

That is why in this paper, a PMS is proposed to keep the battery under service for longer period of time by controlling the state of charge (SOC) of the battery. The SOC control is done by (*i*) turning on the fuel cell and the electrolyser at proper time and (*ii*) deciding how much power will be generated or consumed by the fuel cell or the electrolyser, respectively. Both of these decision taken based on SOC. Simultaneously, proposed PMS ensures smooth and satisfactory operation of the fuel cell and the electrolyser in co-ordination with the battery. In order to avoid low current density in the electrolyser and frequent start-ups and shut-downs of the fuel cell, the proposed PMS defines the minimum amount of power to be absorbed or generated by them. As the fuel cell requires time for start-up and taking up the load demand, it is started and floated to DC bus prior to actual demand comes. Therefore, limitation of one storage system can be compensated by other storage system. By doing so, the DC link voltage as well as AC side voltage profile can be improved even though there is wide variation in source and load side.

2. STRUCTURE OF MICROGRID

The overall configuration of the isolated DC microgrid is shown in Fig. 1, in which, 6 *k*W PMSG based WECS, 2.4 *k*W PVECS, 10 A-hr battery, 5 *k*W fuel cell and 5 *k*W aqua electrolyser are interfaced with a common 300 V DC bus through power electronics converter circuits. Power is fed to load through three phase PWM inverter and LC filter circuits. The maximum power rating of battery buck boost converter (P_{b_max}) is 2 *k*W.

3. POWER MANAGEMENT

The power balance equation for the system is given by: $\Delta P = P_{gen} - (P_{load} + P_{loss})$; where, $P_{gen} = (P_{wind} + P_{pv})$; and ΔP is the amount of mismatch power between generation from intermittent sources and load plus losses. The power difference between RES and load is given by: $P_{diff} = (P_{gen} - P_{load}) = (\Delta P + P_{loss})$.

The ΔP amount of power needs to be managed by use of storage and backup to maintain the power balance in the system which is very important for maintaining DC link voltage and simultaneously voltage and frequency of the microgrid. The function of this power management is to ensure the reliable operation of the microgrid by satisfying following two criteria: (*i*) to store ΔP amount of power in the battery and the electrolyser, so as to avoid frequent overcharge condition of the battery and low current density situation in the electrolyser (*ii*) to generate ΔP amount of power from the battery and the fuel cell, so as to avoid frequent undercharge condition of the battery and frequent start up and shut down of the fuel cell.

The power management unit is operated based on following conditions:

Condition I: $\Delta P > 0$; if $|\Delta P| \geq [P_{b\_max}\ x\ (1 - SOC)]$ *k*W, the electrolyser starts consuming power, otherwise, the battery stores surplus power through charging based on SOC.

Condition II: $\Delta P < 0$; similarly, if $|\Delta P| \geq [P_{b\_max}\ x\ SOC]$ *k*W the fuel cell starts generating power, otherwise, the battery supplies required power through discharging based on SOC.

Condition III: $\Delta P = 0$; neither the fuel cell nor the electrolyser is required to operate as per power management strategy.

The amount of power generated by the fuel cell and consumed by the electrolyser under different conditions are given in the following table:

Table 1

<table>
<tr><th></th><th><i>Case I: 0 < SOC ≤ 0.3</i></th><th><i>Case II: 0.3 < SOC < 0.8</i></th><th><i>Case III: 0.8 ≤ SOC < 1.0</i></th></tr>
<tr><td rowspan="2">Condition I :
$\Delta P > 0$</td><td colspan="3">$P_{fc} = 0$</td></tr>
<tr><td colspan="2">$P_{elect} = |\Delta P| - \{P_{b\_max}\ x\ (1 - SOC)\}$
and
$0.5\ kw \leq P_{elect} \leq 5\ kw$</td><td>$P_{elect} = |\Delta P|$
and
$0.5\ kw \leq P_{elect} \leq 5\ kw$</td></tr>
<tr><td rowspan="2">Condition II:
$\Delta P < 0$</td><td>$P_{fc} = |\Delta P|$;
and
$0.5\ kw \leq P_{fc} \leq 5\ kw$;</td><td colspan="2">$P_{fc} = |\Delta P| - (P_{b\_max}\ x\ SOC)$
and
$0.5\ kw \leq P_{fc} \leq 5\ kw$</td></tr>
<tr><td colspan="3">$P_{elect} = 0$</td></tr>
<tr><td rowspan="2">Condition III:
$\Delta P = 0$</td><td colspan="3">$P_{fc} = 0$</td></tr>
<tr><td colspan="3">$P_{elect} = 0$</td></tr>
</table>

4. CONTROL STRATEGIES

For isolated microgrid, droop control technique of PWM inverter is adopted to control AC side voltage, frequency, active and reactive power flow. Extraction of maximum power from WECS and PVECS is done by controlling PWM pulses of respective DC-DC converters using MPPT technique. Whereas, Battery charging and discharging is controlled by buck boost converter. The operation of fuel cell and electrolyser are controlled based on SOC condition of battery. The complete control of microgrid is explained in following sections.

4.1. Control of PWM Inverter

The main objective to inverter controller is to control the magnitude and frequency of the inverter output voltage. This is done by controlling active and reactive power flow through inverter. For controlling magnitude (V) and frequency (ω) of AC output voltage of inverter, a droop control technique is used [17] as shown in Fig. 2. This droop control technique sets the reference magnitude V* and frequency ω* of inverter output voltage corresponding to change in voltage ΔV and frequency Δω, due to change in active and reactive power of the load. The P-ω and Q-V droop characteristics is given by

$$\omega^* = \omega_{rated} - \Delta\omega; \ \Delta\omega = K_P \times P_{inv} \tag{1}$$

$$V^* = V_{rated} - \Delta V; \ \Delta V = K_Q \times Q_{inv} \tag{2}$$

where, K_P and K_Q are droop coefficients. The *d-q* axis voltage references (V_d* and V_q*) are obtained using reference generator block [18]. The inner voltage and current control loop controls the output voltage (V_{dq}) and current (I_{dq}) of inverter as shown in Fig. 2.

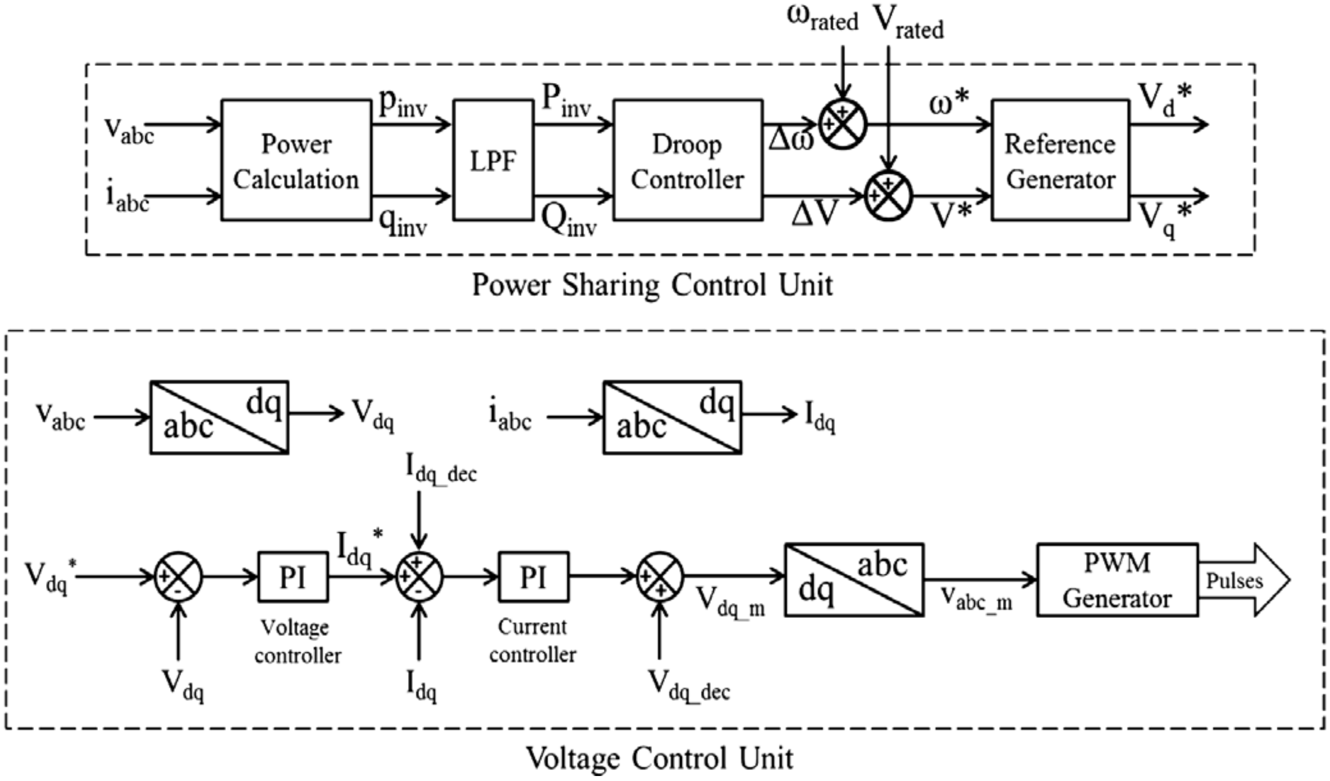

Figure 2: Inverter control strategy

4.2. DC Link voltage control

DC link voltage tries to vary when there is mismatch between supply and demand of real power in DC bus. Therefore, a proper real power management is required to maintain the DC link voltage (V_{dc}) at constant value. Battery plays an important role in DC link voltage control using DC link voltage controller as shown in Fig. 3 (*a*). During transient conditions, battery storage acts as the systems' slack-node, which means that surplus and shortage of power is compensated by the battery storage [1]. Apart from the battery, fuel cell and electrolyser also help to minimise the DC link voltage fluctuation, using their respective current controller as shown in Fig. 3 (*b*) & (*c*). The reference current of fuel cell (I_{fc}*) and electrolyser (I_{elect}*) controllers are obtained from power management unit.

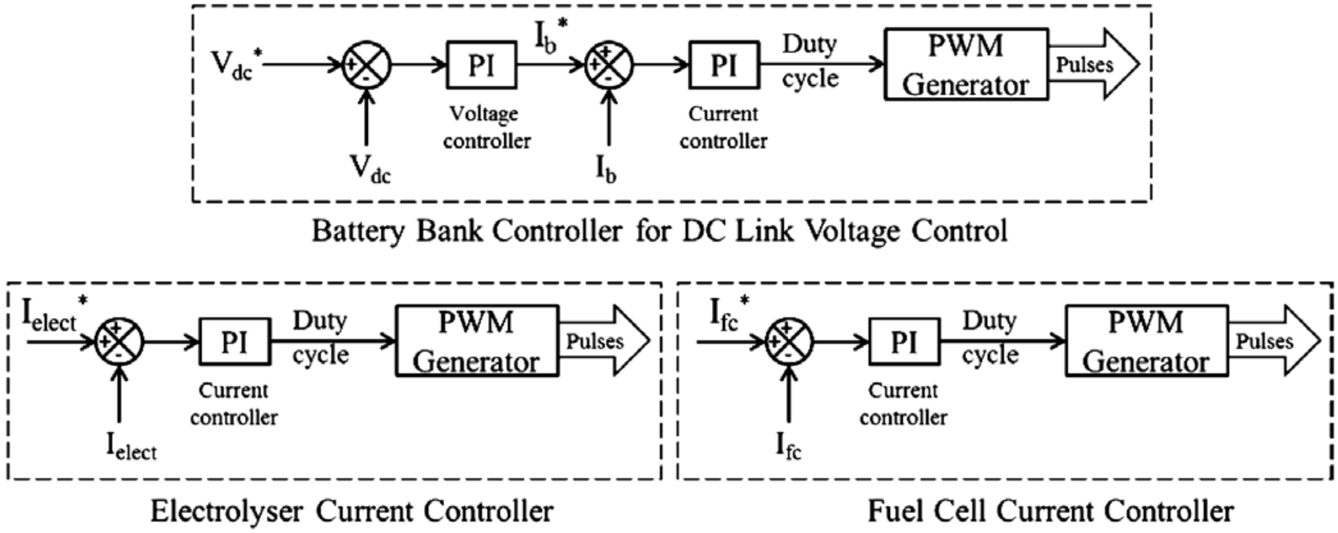

Figure 3: Controllers for the DC link voltage and the fuel cell - electrolyser current

4.3. MPPT Control

Objective of this control strategy is to extract maximum power from WECS and PVECS [15, 16] under varying wind speed and solar irradiation. The MPPT control strategies for PVECS and WECS generate duty cycle for DC-DC and AC-DC PWM converters respectively as shown in Fig. 4.

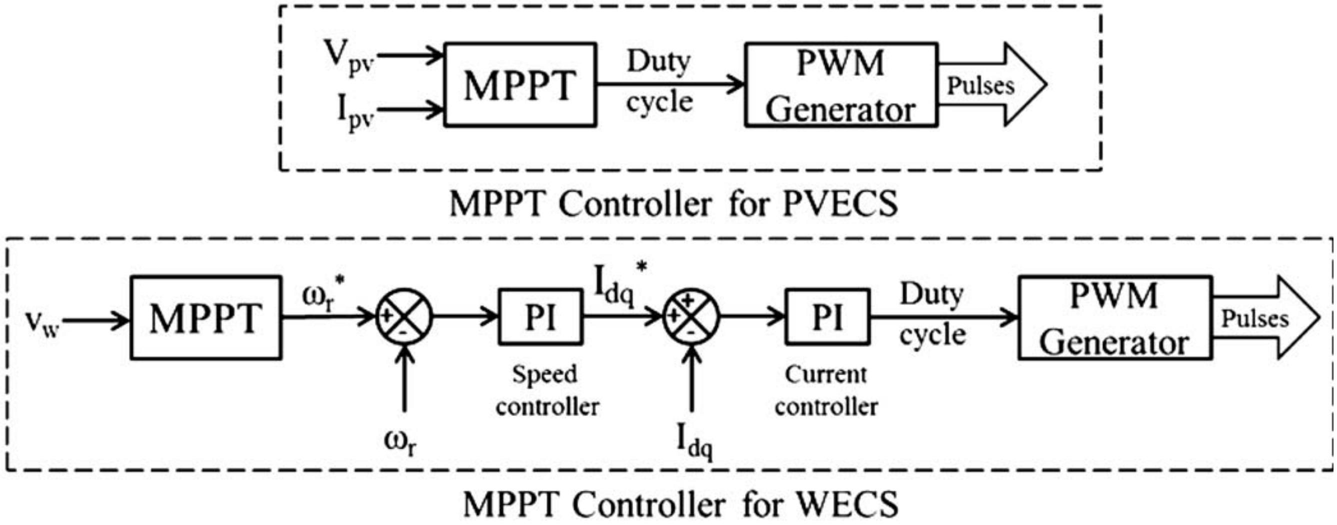

Figure 4: MPPT controller for PVECS and WECS

5. RESULTS AND DISCUSSION

In order to analyse the performance of proposed control and power management technique for the isolated microgrid under fluctuation of wind speed, solar irradiation, and wide load variations, a simulation study is carried out using MATLAB / SIMULINK. The complete proposed model of microgrid is simulated considering dynamic variation of wind speed within 20% of its rated value, 60% variation of rated solar irradiation and step load variation between 50% to 100% of its rated value, with 50% initial SOC.

The fig. 5(*a*) shows the variation of power generation from different DERs of MG along with load demand. Fig. 5(*b*) shows the power mismatch (ΔP) between generation from renewable resources (wind & solar PV) and load including losses. Corresponding DC link voltage and SOC of battery bank are shown in fig. 5(*c*) and (*d*) respectively.

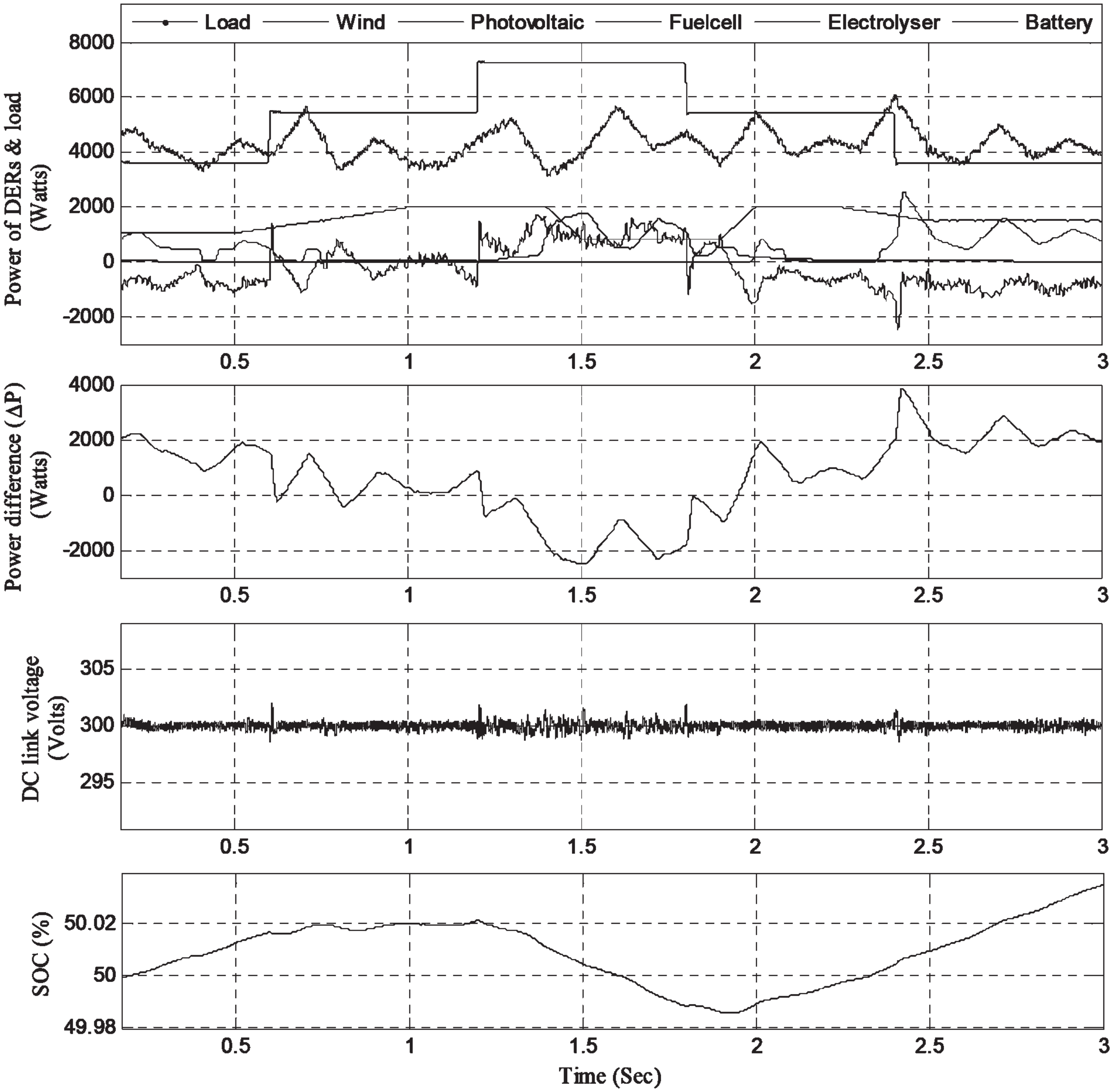

Figure 5: (*a*) Power management, (*b*) Power difference, (*c*) DC link voltage, (*d*) SOC

For better analysis of power management technique whole simulation time is subdivided in to three parts:

Part I : Up to 1sec; the wind power is varied around 4 *k*W. Power from the solar PV is constant around 1 *k*W up to 0.5 sec and then gradually increased to 2 *k*W till 1sec. The load is 3.7 *k*W up to 0.6 sec and at 0.6 sec the load is changed in step to 5.6 *k*W. In this part, when ΔP > 0 and |ΔP| ≥ [2 x (1 – SOC)] *k*W, the electrolyser is allowed to absorb part of surplus power as shown in Fig. 5 (*a*) & (*b*); when ΔP < 0, |ΔP| is very small and is less than [2 x SOC)], the fuel cell is not allowed to generate any power. However, in both the situation, the power balance of the system is managed dynamically by the battery through its charging and discharging [Fig. 5(*a*)]. In this way, the DC link voltage is maintained almost constant using power management, shown in Fig. 5(*c*). At 0.6 sec, when the load is changed from 3.7 *k*W to 5.6 *k*W, due to sudden change of ΔP, the battery current shoots up to cope up with the transient condition which is similar to the inertia of synchronous generator. With the help of DC-link voltage controller and PMS, the DC-link voltage fluctuation is maintained within 1%, as shown Fig. 5(*c*). This reflects good performance of power management unit.

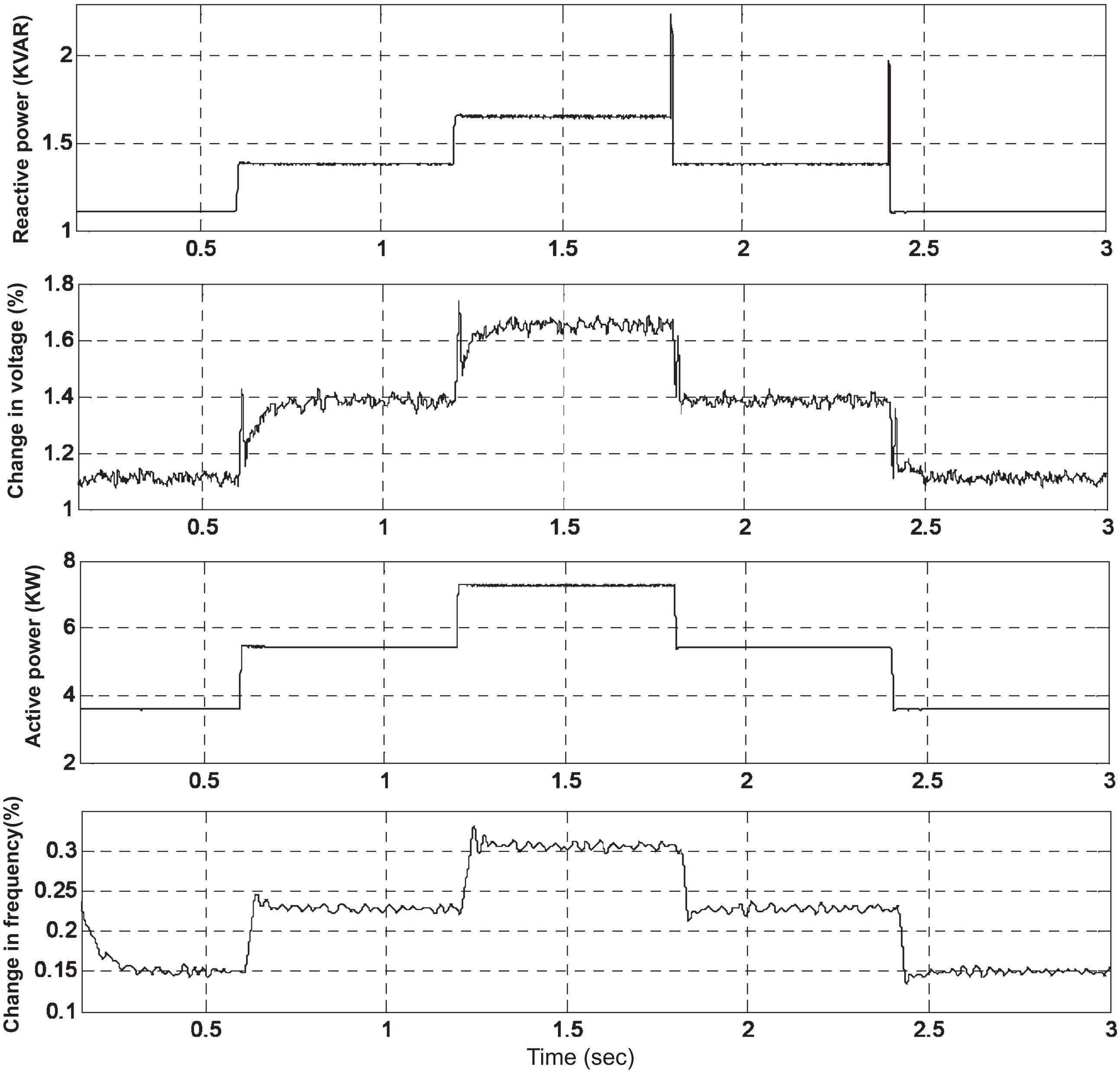

Figure 6: (*a*) Voltage variation at PC and (*b*) Frequency variation at PC

Pat II: From 1 to 2 sec; the wind power is dynamically varied around 4 *k*W. The PV power is constant at 2 *k*W up to 1.4 sec, then gradually dropped to 40 % of its rated value at 1.5 sec and remains constant till 1.9 sec, then again increases to 2 *k*w at 2 sec. At 1.2 sec, load is increased from 5.6 *k*W to 7.5 *k*W and again decreased to 5.6 *k*W at 1.8 sec.

Till 1.2 sec, as ΔP is small, power balance is managed only by the battery. However, the battery current shoots up due to sudden change in ΔP caused by sudden change in load at 1.2 sec. To cope up with the transient condition and maintain the DC link voltage fluction within 1%, the battery current is controlled by dc-link voltage controller [Fig. 5(*c*)]. When solar power is dropped under increased load condition, ΔP < 0 and |ΔP| > [2 x SOC] *k*W, the fuel cell is started to generate and supply the deficit power to maintain the power balance of the system without overburdening the battery as shown in Fig. 5(*a*). This will help in increasing the lifetime of the battery. At 1.8 sec, when load is decreased, the requirement of fuel cell for power generation reduces and the balance power requirement is managed by the battery. By the time, PV power generation is again gradually increased to 2 *k*W, the fuel cell power generation is gradually reduced to zero in order to maintain the power balance of the system.

Part III: From 2 to 3 sec; ΔP is always positive. Whenever $|\Delta P| \geq [2 * (1 - SOC)]\ k$W, the electrolyser stores surplus power in the form of hydrogen as shown in Fig. 5(*a*). By this way PMS maintains the real power balance and minimizes the DC link voltage fluctuation as reflected in Fig. 5(*c*). Therefore, during transient conditions, created by both source and load side dynamics, the variation of DC link voltage is maintained within ±1% of its reference value using SOC based PMS and battery controller. During the operation of the microgrid, the battery SOC [Fig. 5(*d*)] goes neither very high nor very low, which will increase the durability of battery. During ΔP is positive, the battery is charged to increase the SOC level and during ΔP is negative, the battery is discharged to decrease the SOC level.

By using inner loop current and voltage controller, the effective droop control technique regulates the voltage and frequency variation at PC within 2% (0.2 Hz) and 0.35% (2.5 Volts), respectively, under load variation as shown in Fig. 6. The pattern of frequency and voltage variation is similar to the pattern of load active and reactive power variation, respectively.

6. CONCLUSION

In this paper, SOC based power management strategy with coordinated control technique is proposed for an isolated DC microgrid with multiple storage. The proposed scheme helps in maintaining the power balance between generation (solar PV and wind) and load, under simultaneous source and load variation, to minimise the dc-link fluctuation. Coordinated operation of fuel cell - electrolyser and battery, can enhance the durability of battery. Therefore, limitation of one storage system is compensated by other storage system. The effective droop controller is able to maintain the voltage and frequency at PC within permissible limit under varying load condition as well. From the simulation results, it is observed that in the presence of source and load variation, the power management technique with the help of droop controller regulates the AC side voltage and frequency while maintaining the DC link voltage almost constant.

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